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13. ABSTRACT *(Maximum 200 words)*

The focus of the project was to develop advanced Automatic Target Recognition (ATR) algorithms to interface with the existing ATR technology at NGC. As outlined in the project proposal, the specific goals of this project were the following: (1) Development of wavelet-based denoising and compression algorithms by Rice CML for SAR and SONAR images. (2) Development of wavelet-based algorithms for ATR in SAR and SONAR data by Rice CML. (3) Transfer of Rice denoising/compression/detection software to NGC for testing on SAR and SONAR data. (4) Application of Rice software in a real-time demo. (5) Establishment of a password protected Rice CML ATR website to facilitate infor-mation sharing between all parties and technology transfer from Rice to NGC.

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Rice-Northrop Grumman Joint
Real Time Wavelet-Based ATR Project
Final Progress Report to DARPA

Raymond O. Wells, Jr. (Rice), Richard G. Baraniuk (Rice),
and Paul H. Haley (NGC)

October 2000

This is the final report for the DARPA-AFOSR grant F49620-97-0513. It summarizes our research effort over the past three years in Real Time Wavelet-Based ATR. This project was a joint effort between Rice Computational Mathematics Laboratory (CML) and Northrop Grumman Corporation (NGC). The personnel directly involved in this project were (from Rice) Raymond Wells (PI), Richard Baraniuk (co-PI), Jun Tian (research scientist), Vidya Venkatachalam (NGC-supported postdoc), Felix Fernandes (graduate student), and Justin Romberg (graduate student), and (from NGC) Phil Schweizer, Robert Mitchell, Paul Haley (PI), Andrew Miklich, and Mike Hoffelder. Sidney Burrus (co-PI) was actively involved in the project until he became Dean of Engineering at Rice in Summer 1998.

1 Project Goals

The focus of the project was to develop advanced Automatic Target Recognition (ATR) algorithms to interface with the existing ATR technology at NGC. As outlined in the project proposal, the specific goals of this project were the following:

1. Development of wavelet-based denoising and compression algorithms by Rice CML for SAR and SONAR images.
2. Development of wavelet-based algorithms for ATR in SAR and SONAR data by Rice CML.
3. Transfer of Rice denoising/compression/detection software to NGC for testing on SAR and SONAR data.
4. Application of Rice software in a real-time demo.
5. Establishment of a password protected Rice CML ATR website to facilitate information sharing between all parties and technology transfer from Rice to NGC.

2 Research Accomplishments

All goals put forth in the project proposal have been achieved during the course of the last three years. The research has been presented at major conferences (ICASSP, SPIE, ICIP, etc.), and it also appears in several leading journal publications. A listing of recent publications by Rice personnel supported by the DARPA grant is provided at the end of the report. This provides a flavor of the current research effort at Rice.

1. Rice has developed algorithms to perform wavelet-based image *compression* and *denoising*. These algorithms were then incorporated in the preprocessing stage in ATR schemes. The algorithms tested successfully for detection performance using CFAR on SAR and SONAR data provided by NGC. An example of detection performance using the Rice wavelet-based denoising algorithm on SONAR data with ground truths provided by NGC is shown in Figure 1. Figure 2 shows an example of detection performance on the same SONAR data, compressed to a ratio of 40:1.

   Rice has transferred the developed software to NGC for testing on classified and unclassified data. The transfer process has been smooth, with NGC reporting no problems in applying the codes. The routines have tested successfully on actual field data. A rigorous testing and documentation of the results of applying the Rice CFAR denoising/detection algorithm on actual SONAR and SAR data was performed by NGC, as proposed in the last annual project report. A part of this work was presented by Mike Hoffelder at the 14th SPIE Aerosense Conference in Orlando in April 2000 [11].

2. Rice has also developed algorithms for wavelet-based ATR as proposed in the proposal. The main objective here was the classification of clutter in SAR images, for the purpose of prescreening in an ATR scheme. As proposed in the last annual report, Rice has successfully developed a new approach to ATR based on *wavelet-domain hidden Markov trees* (HMTs). This has been applied to SAR data with very good results. Details of this work can be obtained from [12]. In addition, Rice has also developed an algorithm to perform unsupervised SAR image segmentation based on Poisson approximations, which was also presented at the 14th annual SPIE Aerosense conference [13]. Both these approaches have been found by NGC to be very useful for prescreening applications in their ATR schemes. Figure 3 shows an example of the segmentation of a SAR image from the MSTAR data set using both these schemes.

3. Significant progress has been made on research on wavelet-based pseudo power signatures (PPSs) for ATR [15],[16]. PPSs offer invariance to the size, location, and magnitude of targets for potentially more robust detection and classification.

4. Work on optimally shift-invariant, directionally selective complex wavelet bases is progressing satisfactorily with some exciting new results reported [17], [18]. These new wavelet bases are compatible with the CFAR, HMT, and PPS techniques and will endow them with shift-invariance and directional selectivity, thereby improving overall performance.

5. One of the principal goals of this research effort was the deployment of Rice software in real-time ATR applications by NGC. On that front, we note that ICompress, a copyrighted wavelet image compression algorithm developed by Rice CML, has been deployed in a US Navy minehunting system. Northrop Grumman Oceanic Systems in Annapolis, Maryland is incorporating ICompress into the US Navy's AN/AQS-14A Search Sonar System operated from the MH-53E helicopter. The algorithm is being used for compressing side look sonar data for real time transmission from the helicopter to a shore or shipboard station over an HF radio link in minehunting operations. The use of wavelet compression is reducing the transmission time for the sonar snippets from three and a half minutes to under fourteen seconds (successfully using 16 to 1 compression). This upgrade was installed into all US Navy systems in the March-April timeframe.

6. Finally, Rice CML has established a password-protected ATR website with URL `www.cml.rice.edu/atr` to interactively demonstrate new algorithms, educate NGC personnel on new developments, and transfer technology in a smooth and timely fashion.

3 Project milestones

A significant component of the project has been the active interaction between the Rice, NGC, and DARPA personnel by means of a series of meetings, and telephone and email communications. This has resulted in Rice developing algorithms specifically targeted to meeting the needs expressed by the NGC personnel. The joint effort produced three papers [11],[12],[13] presented at the 14th SPIE Aerosense Conference in Orlando, FL, in April 2000. A timeline of the interaction is summarized in Table 1.

During the course of the project, several students were awarded M.S. and Ph.D. degrees. Students who received degrees and were either fully or partially supported

Table 1: ATR project meetings

Event	Date
Paul Haley visit to Rice	November 1996
ATR project kick-off meeting in Washington DC	April 1998
Richard Baraniuk visit to DARPA	June 1998
Jun Tian and Vidya Venkatachalam visit to NGC	October 1998
Paul Haley visit to Rice	January 1999
Raymond Wells visit to DARPA	February 1999
Rice-NGC meeting with DARPA	April 1999
NGC visit to Rice	June 1999
DARPA, AFOSR and NGC visit to Rice	February 2000

by this grant, or worked in areas complementary to the grant research areas are:

- Matthew Crouse - Ph.D. (May 1999)
- Roger Claypoole - Ph.D. (May 2000)
- Justin Romberg - M.S. (May 1999)
- Ramesh Neelamani - M.S. (May 1999)

4 List of Publications (1997-2000)

1. J. Romberg, H. Choi, R. G. Baraniuk, and N. Kingsbury, "Multiscale classification using complex wavelets and hidden Markov tree models," *IEEE International Conference on Image Processing (ICIP),* Vancouver, Canada, Oct. 2000.

2. H. Choi, K. Berkner, and R. G. Baraniuk, "Statistical image processing using localized Besov space properties," *SPIE Technical Conference on Wavelet Applications in Signal and Image Processing VIII,* San Diego, CA, July 2000.

3. J. Ribeiro, R. H. Riedi, M. S. Crouse and R. G. Baraniuk, "Multiscale Queuing Analysis of Long-Range-Dependent Network Traffic," To appear in *Proc. IEEE INFOCOM'00,* Tel-Aviv, Israel.

4. R. Neelamani, R. Riedi, H. Choi, and R. G. Baraniuk, "Multiscale shape and texture analysis of images," *SPIE Technical Conference on Wavelet Applications in Signal and Image Processing VIII (invited talk),* San Diego, CA, July 2000.

5. J. Romberg, R. Riedi, H. Choi, and R. G. Baraniuk, "Multiplicative multiscale image analysis and modeling," *SPIE Technical Conference on Wavelet Applications in Signal and Image Processing VIII,* San Diego, CA, July 2000.

6. T. Dorney, S. Bhashyam, A. Doran, H. Choi, P. Flandrin, and R. Baraniuk, "Edge localized image sharpening via reassignment with application to computed tomography," *SPIE Technical Conference on Mathematical Modeling, Estimation, and Imaging,* San Diego, CA, July 2000.

7. H. Choi, J. K. Romberg, N. Kingsbury, and R. G. Baraniuk, "Hidden Markov tree modeling of complex wavelet transforms," in *Proc. IEEE international conference on Acoustics, Speech, and Signal Processing (ICASSP),* Istanbul, Turkey, June 2000.

8. R. G. Baraniuk, "Optimal Tree Approximation using Wavelets," *Proc. SPIE Technical Conference on Wavelet Applications in Signal Processing VII,* Denver, July 1999.

9. H. Choi and R. G. Baraniuk, "Multiscale document segmentation using wavelet-domain hidden Markov models," in *Proc. IST/SPIE's 12th Annual International Symposium - Electronic Imaging 2000, Science and Technology,* San Jose, CA, January, 2000.

10. J. Tian, R. G. Baraniuk, R. O. Wells, Jr., D. M. Tan, and H. R. Wu, " Wavelet folding and decorrelation across scale," in *Proc. IEEE international conference on Acoustics, Speech, and Signal Processing (ICASSP)*, Istanbul, Turkey, June 2000.

11. M. Hoffelder and J. Tian, "Automatic Target Recognition (ATR) performance using wavelet compression on Synthetic Aperture Radar (SAR) imagery," in *Proc. SPIE's 14th Annual International Symposium on Aerospace/Defense Sensing, Simulation, and Control (AeroSense)*, Orlando, FL, April, 2000.

12. V. Venkatachalam, H. Choi, and R. G. Baraniuk, "Multiscale SAR image segmentation using wavelet-domain hidden Markov tree models," in *Proc. SPIE's 14th Annual International Symposium on Aerospace/Defense Sensing, Simulation, and Control (AeroSense)*, Orlando, FL, April, 2000.

13. V. Venkatachalam, R. D. Nowak, R. G. Baraniuk, and Mario A. T. Figueiredo, "Unsupervised SAR image segmentation using recursive partitioning," in *Proc. SPIE's 14th Annual International Symposium on Aerospace/Defense Sensing, Simulation, and Control (AeroSense)*, Orlando, FL, April, 2000.

14. H. Choi and R. G. Baraniuk, "Multiscale Image Segmentation using Wavelet-Domain Hidden Markov Models," submitted to *IEEE Transactions on Image Processing*, October 1999.

15. V. Venkatachalam, "Image classification using Pseudo Power Signatures," *IEEE International Conference on Image Processing (ICIP)*, Vancouver, Canada, Sep. 2000.

16. V. Venkatachalam, "Pseudo Power Signatures for image classification: SVD and projector approaches," *SPIE Technical Conference on Wavelet Applications in Signal and Image Processing VIII*, San Diego, CA, July 2000.

17. F. C. A. Fernandes, R. van Spaendonck, Mark Coates, and C. S. Burrus, "Directional complex-wavelet processing," *SPIE Technical Conference on Wavelet Applications in Signal and Image Processing VIII*, San Diego, CA, July 2000.

18. R. van Spaendonck, F. C. A. Fernandes, Mark Coates, and C. S. Burrus, "Non-redundant , directionally selective, complex wavelets," *IEEE International Conference on Image Processing (ICIP)*, Vancouver, Canada, Sep. 2000.

19. R. van Spaendonck, F. M. Hindriks, F. C. A. Fernandes, and G. G. Drijkoningen, "Three-dimensional attributes for seismic interpretation," *70th annual meeting SEG*, Aug. 2000.

20. J. K. Romberg, H. Choi, and R. G. Baraniuk, "Shift-invariant denoising using wavelet-domain hidden Markov trees," in *Proc. 33rd Asilomar Conference*, Pacific Grove, CA, Oct. 1999.

21. B. Hendricks, H. Choi, and R. G. Baraniuk, "Analysis of texture segmentation using wavelet-domain hidden Markov models," in *Proc. 33rd Asilomar Conference*, Pacific Grove, CA, Oct. 1999.

22. M. Bayram, R. G. Baraniuk, "Multiple Window Time-Varying Spectrum Estimation," Chapter in the Cambridge University Press Volume on the Isaac Newton Institute program on Nonlinear and Nonstationary Signal Analysis, 2000.

23. R. Neelamani, H. Choi, and R. G. Baraniuk, "Wavelet-domain regularized deconvolution for ill-conditioned systems," in *Proc. IEEE International Conference on Image Processing (ICIP)*, Kobe, Japan, Oct. 1999.

24. H. Choi and R. G. Baraniuk, "Multiple wavelet-domain image denoising by Besov projections," in *Proc. IEEE International Conference on Image Processing (ICIP)*, Kobe, Japan, Oct. 1999.

25. I. Magrin-Chagnolleau, H. Choi, R. V. Spaendonck, P. Steeghs, and R. G. Baraniuk, "Multiscale texture segmentation of dip-cube slices using wavelet-domain hidden Markov trees," in *Proc. 69th SEG Meeting*, Houston, Texas, 1999.

26. H. Choi and R. G. Baraniuk, "Wavelet-domain statistical models and Besov spaces," in *Proc. SPIE Technical Conference on Wavelet Applications in Signal Processing VII*, Denver, CO, July 1999.

27. J. Romberg, H. Choi and R. G. Baraniuk, "Bayesian tree-structured image modeling," in *Proc. SPIE Technical Conference on Mathematical Modeling, Bayesian Estimation, and Inverse Problems*, Denver, CO, July 1999.

28. H. Choi and R. G. Baraniuk, "Image segmentation using wavelet-domain classification," in *Proc. SPIE Technical Conference on Mathematical Modeling, Bayesian Estimation, and Inverse Problems*, Denver, CO, July 1999.

29. H. Choi and R. G. Baraniuk, "Information-theoretic Analysis of Besov Spaces," *Proceedings of SPIE Technical Conference on Wavelet Applications in Signal and Image Processing VIII*, San Diego, August 2000.

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37. M. S. Crouse, R. D. Nowak, and R. G. Baraniuk, "Wavelet-based Statistical Signal Processing using Hidden Markov Models," *IEEE Transactions on Signal Processing* (Special Issue on Theory and Applications of Filter Banks and Wavelet Transforms), Vol. 46, No. 4, pp. 886–902, April 1998.

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39. R. Neelamani, H. Choi, and R. G. Baraniuk, "Wavelet-Based Deconvolution for Ill-Posed Systems," *SPIE Technical Conference on Wavelet Applications in Signal Processing VII*, Denver, July 1999.

40. R. L. Claypoole and R. G. Baraniuk, "Lifted Nonlinear Wavelet Transforms," *SPIE Technical Conference on Wavelet Applications in Signal Processing VII*, (Invited session on multirate filter bank applications), Denver, July 1999.

41. H. Choi and R. G. Baraniuk, "Wavelet Statistical Models and Besov Spaces," *SPIE Technical Conference on Wavelet Applications in Signal Processing VII*, Denver, July 1999.

42. H. Choi and R. G. Baraniuk, "Image Segmentation using Wavelet-domain Classification," *SPIE Technical Conference on Mathematical Modeling, Bayesian Estimation, and Inverse Problems*, Denver, July 1999.

43. J. Romberg, H. Choi, and R. G. Baraniuk, "Bayesian Tree-Structured Image Modeling," *SPIE Technical Conference on Mathematical Modeling, Bayesian Estimation, and Inverse Problems*, Denver, July 1999.

44. J. K. Romberg, H. Choi and R. G. Baraniuk, "Bayesian Wavelet Domain Image Modeling using Hidden Markov Trees" to appear in *Proc. IEEE International Conference on Image Processing - ICIP'99*, Kobe, Japan, October 1999.

45. V. J. Ribeiro, R. H. Riedi, M. S. Crouse, and R. G. Baraniuk, "Wavelet-based Modeling for Queuing of Non-Gaussian LRD Network Traffic," *ACM SIGMETRICS'99*, Atlanta, May 1999.

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53. R. L. Claypoole, R. G. Baraniuk, and R. D. Nowak, "Non-Linear Wavelet Transforms using Lifting," *IEEE-SP International Symposium on Time-Frequency and Time-Scale Analysis*, Pittsburgh, October 1998.

54. H. Choi and R. G. Baraniuk, "Analysis of Wavelet-Domain Wiener Filters," *IEEE-SP International Symposium on Time-Frequency and Time-Scale Analysis*, Pittsburgh, October 1998.

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60. R. L. Claypoole, R. G. Baraniuk, and R. D. Nowak "Adaptive Wavelet Transforms via Lifting," *IEEE International Conference on Acoustics, Speech and Signal Processing — ICASSP98*, Seattle, May 1998.

61. R. L. Claypoole, G. Davis, W. Sweldens, and R. G. Baraniuk, "Adaptive Wavelet Transforms for Image Coding using Lifting," *Digital Compression Conference*, Snowbird, UT, March 1998.

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63. H. L. Resnikoff, J. Tian, R. O. Wells, Jr., "Biorthogonal Wavelet Space: Parametrization and Factorization," invited talk, *AMS 1999 Spring Central Section Meeting*, March 1999.

64. J. Tian and R. O. Wells, Jr., "Joint Compression and Detection in the Wavelet Domain," to appear in *Proc. 42nd Midwest Symposium on Circuits and Systems*, July 1999.

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78. F. C. A. Fernandes and C. S. Burrus, "Multiwavelet systems with disjoint multiscaling functions," *IEEE International Conference on Acoustics, Speech and Signal Processing —ICASSP99*, Phoenix, March 1999.

79. K. Berkner and R. O. Wells Jr., "A new Hierarchical Scheme for Approximating the Continuous Wavelet Transform with Applications to Edge Detection," to appear in *IEEE Signal Proc. Letters.*

80. K. Berkner and R. O. Wells Jr., "Wavelet Transforms and Denoising Algorithms," *Proc. of the 32nd Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, November 1998.

81. K. Berkner and R. O. Wells Jr., "A Fast Approximation to the Continuous Wavelet Transform with Applications," *Proc. of the 31st Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, November 1997.

82. K. Berkner and R. O. Wells Jr., "Denoising via Nonorthogonal Wavelet Transforms," Preprint, presented at the *NSF-CBMS Regional Research Conference on Wavelet Analysis as a Tool for Computational and Harmonic Analysis*, 1998.

83. K. Berkner, "On spectra of stationary wavelet-based processes," to be submitted to *IEEE Trans. Signal Processing.*

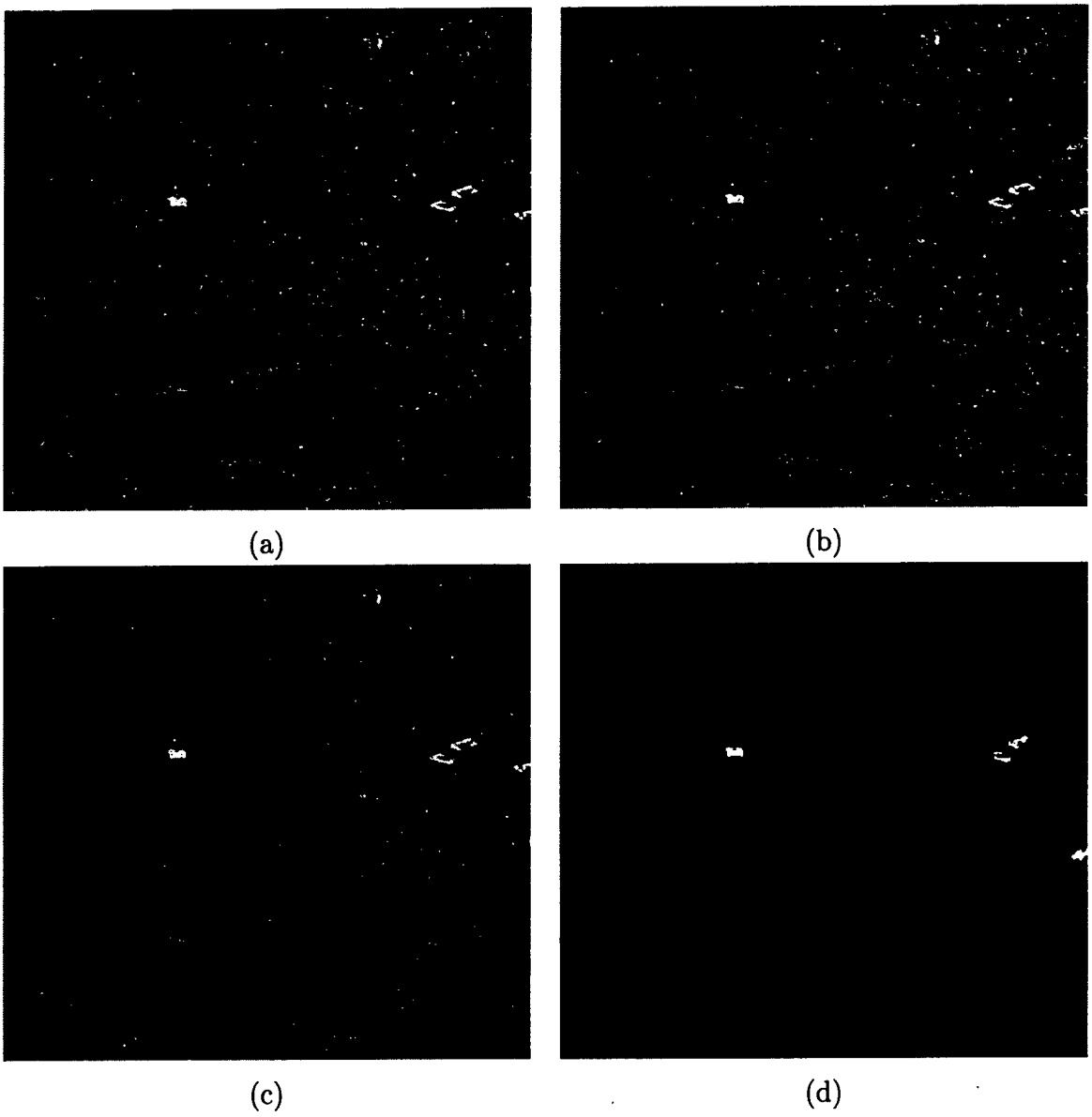


Figure 1: *(a) Original SONAR image, (b) With ground truth, (c) Denoised SONAR image, (c) CFAR Detection performance using denoised image*

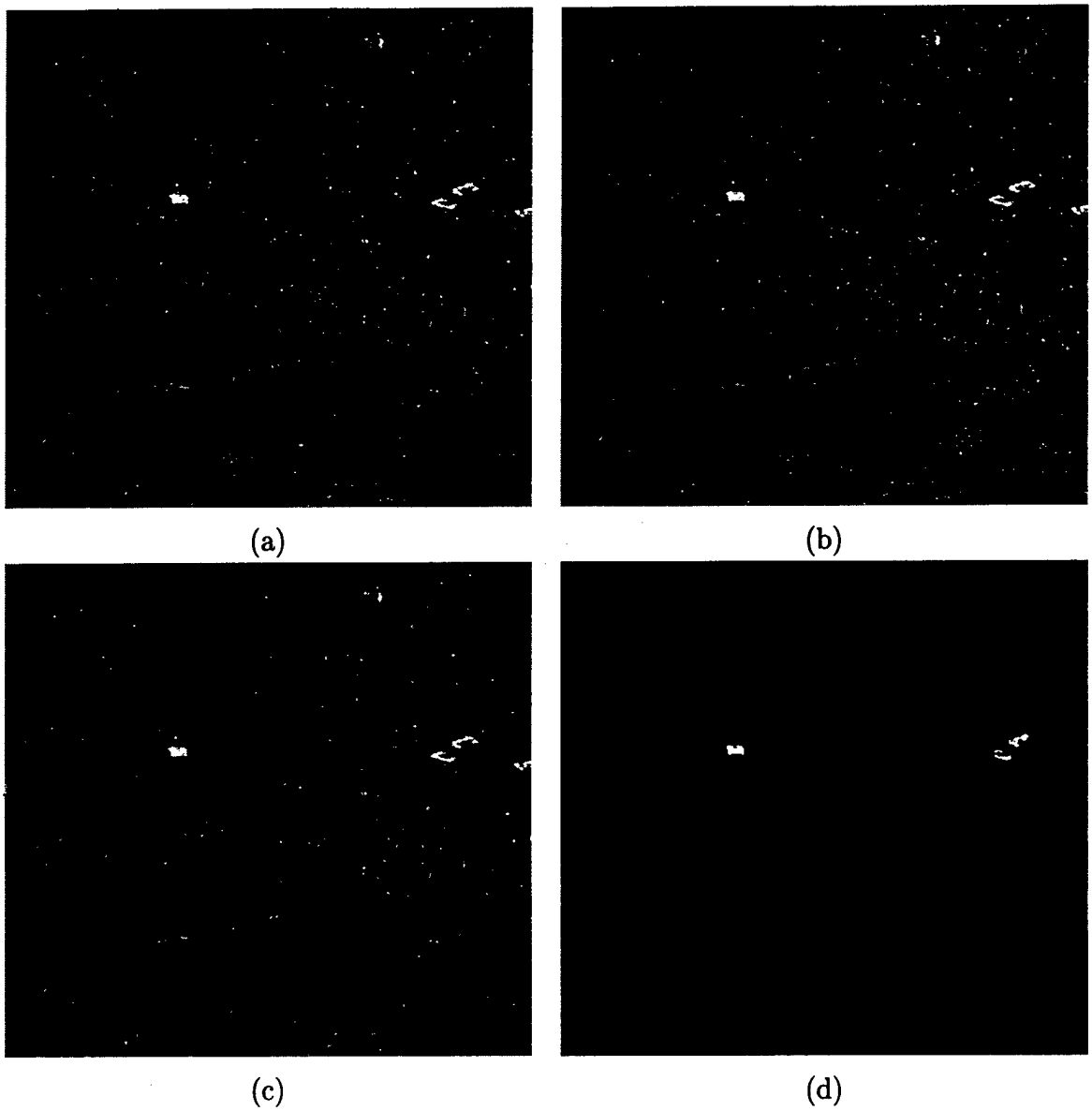
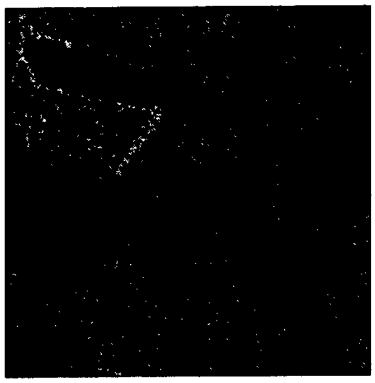
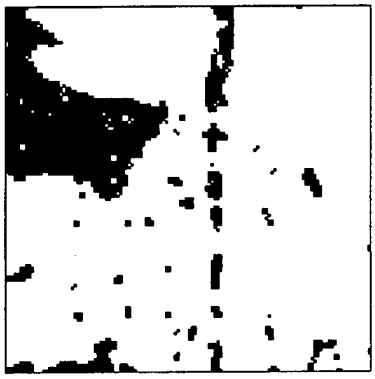


Figure 2: *(a) Original SONAR image, (b) With ground truth, (c) 40:1 Compressed SONAR image, (c) CFAR Detection performance using compressed image*



(a)



(b)

(c)

Figure 3: *(a) Original SAR MSTAR data HB06170 containing forest and field imagery, (b) Segmented data using HMT, (c) Segmented data using Poisson approxomations*